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Flip-chip package for pressure sensors with operation-temperatures up to 500 °C

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Abstract

This work presents a novel flip-chip-package for pressure sensors that operate at very high temperatures. The packaging method is based on glass-soldering, gold stud-bumping and low-CTE-ceramic-substrates. The investigated sensor substrates were aluminiumnitride (AlN), siliconnitride (Si_3N_4) and a ceramic based on $ZrSiO_4$ that was specific matched to the thermal-mechanical behavior of silicon. The sensor-element consists of thin-film platinum layers on a DRIE-etched silicon membrane. For the protection of the functional layer and the contact-metallization, the sensors are assembled using the developed flip-chip-method. Afterwards, the assemblies were packaged in a steel housing that allows a characterization of the sensors in a high temperature and high pressure atmosphere. Subsequently, the pressure sensitivity and cross-sensitivity on temperature of the sensor output signal was characterized with a special designed test set-up. Results for the sensor offset, the linearity and the signal-change over temperature are given. The effect of long-term storage at 500 °C and thermal shock-cycling with a temperature difference of 470 K on the output-signal and on the reliability of the sensor package was analyzed. Sensors of the most appropriate assembly-configuration survived 500 hours of long-term storage and 500 cycles without detection of a failure.

Key words: pressure sensor, flip-chip package, ceramics, finite-element-method, high temperature

Introduction

Transducers that can operate in harsh environments with high temperatures (HT) around 500 °C can contribute to optimize ignition-processes in motors, turbines or chemical reactors [1]. Electronic devices that can sustain HT-peaks and are able to operate permanently at 500 °C are part of actual research projects. In the field of aircraft, industrial facilities and automotive applications there is the demand to collect data about the condition of processes machines, systems or the environment under extreme rough atmospheres. In the past, several approaches for robust HT-sensors based on silicon carbide or platinum with structures in the micron range were developed to obtain the advantages of MEMS-devices also under these extreme harsh operation conditions [2], [3]. Despite the low number of high temperature stable sensor systems that can actually work permanently at 500 °C, there are various applications where such sensors can be applied. The reliability of the already existing HT-sensor-elements and their assembly and packaging technologies has to be further developed and improved [4]. Only few studies are published that address the reliability of high temperature packaging technologies [5] - [7]. In the past we developed robust assembly processes and investigated the reliability of these methods and technologies [8]. In this study we demonstrate the novel approach for a pressure sensor package that is functional at temperatures up to 500 °C. Fig. 1 exhibits a flip-chip sensor-assembly that is integrated in a steel housing made of Inconel.

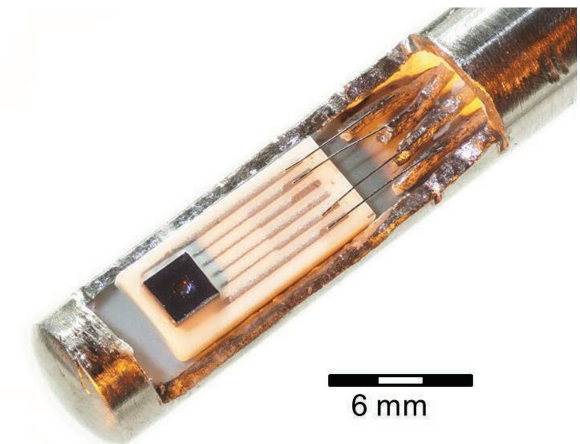

Fig. 1. Packaged high temperature pressure sensor in a steel housing

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Sensor element

We developed absolute pressure sensors based on silicon-dies processed with thin-film technology. The chosen sensor principle was a Wheatstone-bridge of piezoresistive platinum meanders with structure widths of 5 µm, located on a pressure sensitive silicon-membrane. For electrical isolation of the functional layer, a 2 µm thick layer of SiO_2 was deposited. The 40 µm thick circular diaphragm was etched with a DRIE-ICP process. The maximum operation pressure for the designed devices is 20 bar.

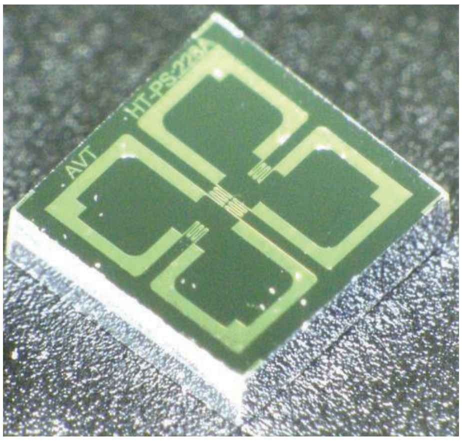

Fig. 2. Platinum based pressure sensor

In Fig. 2 a pressure sensor is shown after the dicing process. This study focuses on the optimized sensor-design A.

Flip-chip packaging

The materials choice of the assembly components is of fundamental importance for the later reliability of the sensor-system. The materials should be stable at HT with a minimal tendency for corrosion and compatible to each other regarding chemical interaction, building of intermetallic phases and thermal-mechanical properties. In earlier studies we identified the low-CTE ceramics AlN and Si_3N_4 in combination with a low-CTE borosilicate glass-solder as well suited components for the assembly of the developed silicon sensor-dies [8]. Furthermore, we investigated a specific matched ceramic based on $ZrSiO_4$ which was developed and provided by the Robert Bosch GmbH. In Tab. 1 important material properties of the investigated sensor substrates are summarized.

Tab. 1: Material properties of the utilized substrates

	Silicon	AlN	Si_3N_4	$ZrSiO_4$
$\alpha_{20\text{-}300}$[1] [ppm/K]	3.2	5.1	2.8	~3.3
λ [W/mK]	150	170	70	5,8
E [GPa]	161	310	314	~200

[1] Coefficient of thermal expansion (CTE)

The ceramics were metallized with conduction-lines and bond-pads by a screen-printing- and firing-process of a temperature stable PtAu-thick-film. The interconnection of the sensor-elements was carried out with gold stud-bumps made with a ball-wedge-bonder from *Delvotek*. Fig. 3 presents Au-bumps after the bonding on the substrate-metallization.

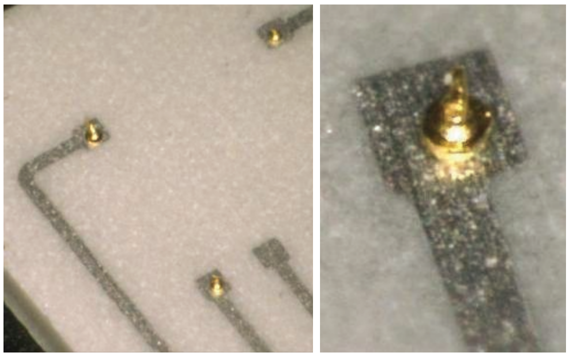

Fig. 3. Gold stud-bumps on a Si_3N_4-substrate

The major steps of the packaging process are described in a schematic cross-section of the assembly in Fig. 4. The glass-soldering after the chip-mounting was carried out at 700 °C in air.

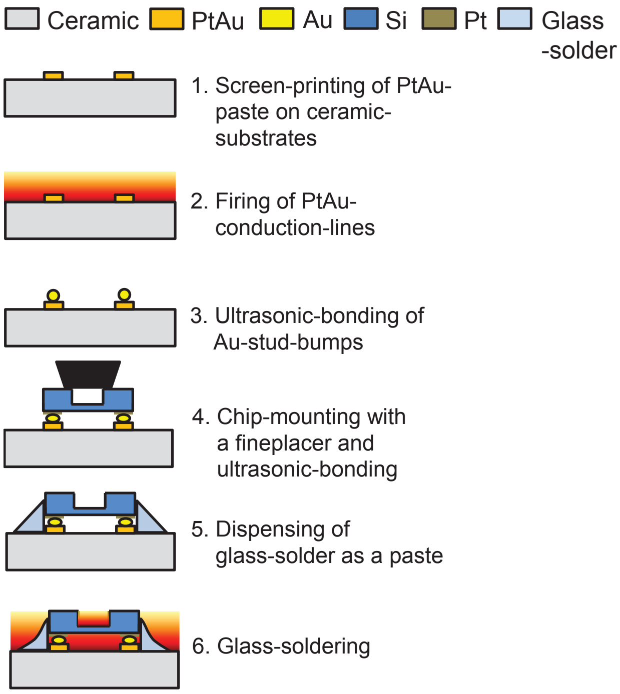

Fig. 4. Schematic of the flip-chip packaging process

After the glass-soldering, the cavity under the sensor-membrane is sealed. For the analysis of the solder-process-quality and the appearance of the micro-bumps after the processing, we conducted metallographic cross-sections of the sensors. Fig 5 exhibits a micrograph of a section made from a flip-chip packaged pressure sensor with a $ZrSiO_4$-substrate.

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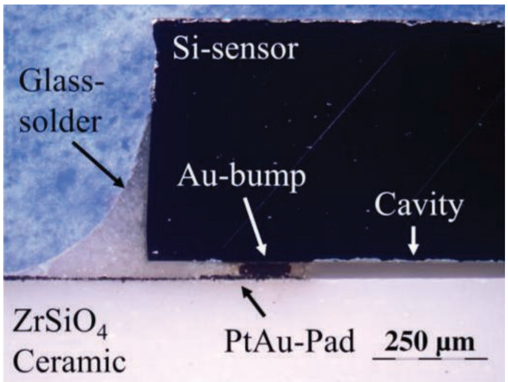

Fig. 5. Cross-section of a sensor-assembly

Sensor characterization

The assembled sensors were integrated in an Inconel steel housing, shown in Fig. 1. With this package the sensor-signal was characterized in terms of pressure- and temperature-sensitivity. Fig. 6 exhibits the specifically constructed pressure chamber and set-up for the sensor-characterization which is capable to sustain a maximum pressure of 250 bar and temperatures up to 500 °C.

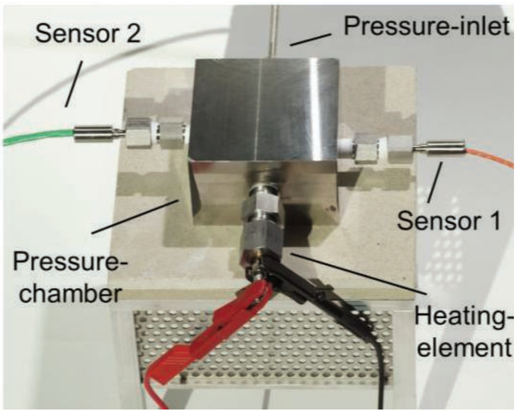

Fig. 6. Set-up for sensor characterization

For the analysis of the package-reliability, we utilized an infra-red heating chamber, shown in Fig. 7. With this set-up, heating-ramps of over 150 K/min were performed with a temperature difference of 470 K.

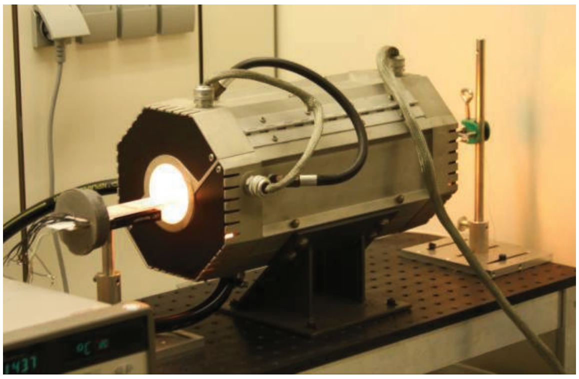

Fig. 7. High-temperature chamber for reliability testing of the sensor-assemblies

After the thermal shock-cycling, the sensor signal was analyzed by electrical testing of the devices and failure effects like cracks or delamination were investigated optically.

Results and discussion

The results for the pressure dependency of the output-bride-signal U_B for a flip-chip-sensor with $ZrSiO_4$-substrate at room temperature are presented in Fig 8.

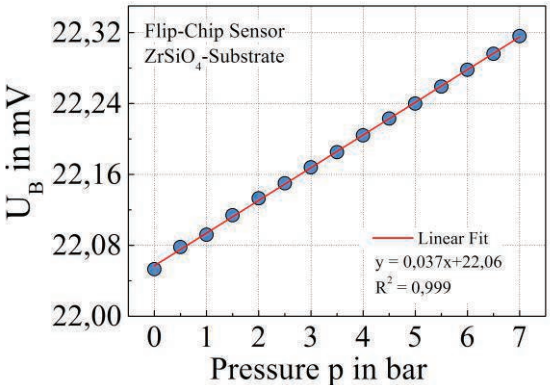

Fig. 8. Results for the pressure sensitivity at 20 °C

A nearly linear pressure sensitivity was obtained with a value of 37 µV/V·bar. We characterized the sensors up to 250 °C and observed a slight increase of the sensitivity at retaining linearity. The temperature cross-sensitivity of the sensor was -2,57 µV/V·K.

We investigated the long-term stability and the reliability under temperature-cycles with the described test-set-up.

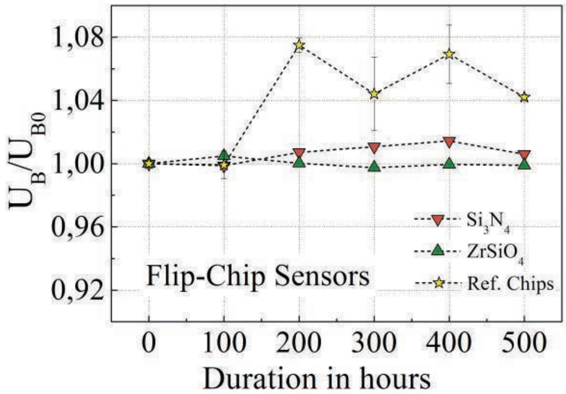

Fig. 9. Signal-shift after HT-storage at 500 °C

The results for the normalized sensor-bridge voltage U_B/U_{B0} over long-term storage of devices with Si_3N_4 and $ZrSiO_4$ were compared to bare sensor-dies as reference chips and shown in Fig. 9. The temperature drift of the signal over time showed values lower than 2 % for both substrates and was smaller than for the reference chips. For $ZrSiO_4$ the obtained signal-shift was 0.2 %. After the long-term-testing of 4 devices no failure was observed.

In possible application environments of the developed sensor-system like motors or turbines, fast temperature changes with occurring thermal differences of about 450 K are expected. Therefore, the devices were stored in the described set-up for 500 HT-cycles to investigate the reliability of the assemblies under such conditions.

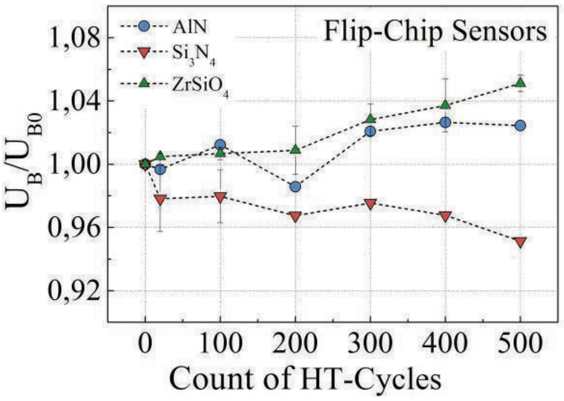

Fig. 10. Signal-shift after HT-cycles with ΔT = 470 K

In Fig. 10 the results of several tested sensor-assemblies are presented. Si_3N_4-devices revealed the highest values of the signal-drift with a maximum of 5 %. These sensor-assemblies also showed the highest number of failures with 2 out of 3 tested devices after 200 shock-cycles.

The detected failure mechanisms of these assemblies were the loss of the sensor-cavity due to cracks in the glass-sealing and delamination of the substrate metallization for Si_3N_4. The sensors with $ZrSiO_4$-substrates showed no failures for 6 tested sensor-assemblies after 500 shock-cycles. In Tab. 2 the results of the study on the sensor reliability are summarized and the assemblies are rated.

Tab. 2: Summarized results for the long-term and cyclic thermal testing of the sensor-assemblies

	AlN	Si_3N_4	$ZrSiO_4$
Tested devices/ Failures	2 / 1	4 / 2	8 / 0
Signal-shift at long-term storage	3 %	2 %	0,2 %
Rating	-	-	++

Conclusion and outlook

The described flip-chip-assembly with $ZrSiO_4$-substrate turned out to be the most appropriate package for the developed pressure sensors. The results concerning the sensitivity, linearity, signal-shift and reliability under rough conditions are promising. We expect thermal-mechanical stresses, induced by the assembly process and mainly influenced by the CTE-mismatch of the sensor-substrate as the major failure cause for the tested assemblies. Performed FEM-simulations revealed high concentrations of tensile stresses at the regions of observed cracks in the glass-sealing of devices with unmatched substrates after shock-cycling. In future research, the $ZrSiO_4$-devices will be stressed with a higher number of shock-cycles to investigate the failure-mechanisms of the stud-bump interconnection.

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